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Acid Sulfate Soils: Their Characteristics, Genesis, Amelioration and Utilization

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Abstract

This paper reviews the characteristics, occurrence, distribution, amelioration and utilization of acid sulfate soils. Emphasis is placed on acid sulfate soils in Thailand and related areas to which references could be found. Data on amelioration relate to rice cultivation, while discussions of management and utilization extend to other crops and fish ponds.

Introduction

Acid sulfate soils are soils with a pH below 4 that is directly or indirectly caused by sulfuric acid formed by oxidation of pyrite. Potential acid sulfate soils are poorly drained soils with a high content of pyrite. The pH of the soil will be neutral or slightly acid in the field. Upon drainage, the soil becomes strongly acidic, which directly affects the growth of plants as a result of aluminum and iron toxicity, and indirectly decreases the availability of phosphorus and other nutrients. Para or pseudo acid sulfate soils are soils in which the acid has been leached out or neutralized to the extent that microbiological activation and root development are no longer hampered and which still show jarosite mottles, high soluble sulfate and high percentage of Al saturation of the clay complex, but not a toxic amount of free or soluble Al.

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Occurrence and Distribution

Acid sulfate soils occur in all climatic zones of the world, from cold and temperate climates to the humid tropics. It seems, however, that they are most extensive in tropical deltas [Kevie 1972].

Acid sulfate soils can be found in all continents except Australia. West Africa, South and Southeast Asia, and the north-east of South America have the largest extents. Considerable areas of acid sulfate soils have been reported in Finland, Sweden, Holland and the United States. The world distribution of acid sulfate soils has been mapped by Kawalec [1972] (Fig. 1) and that of South and Southeast Asia by van Breemen and Pons [1978] (Fig. 2).

Geographically, the majority of acid sulfate soils occurs in coastal areas, developing from recent or semi-recent sediments. They are usually restricted to areas

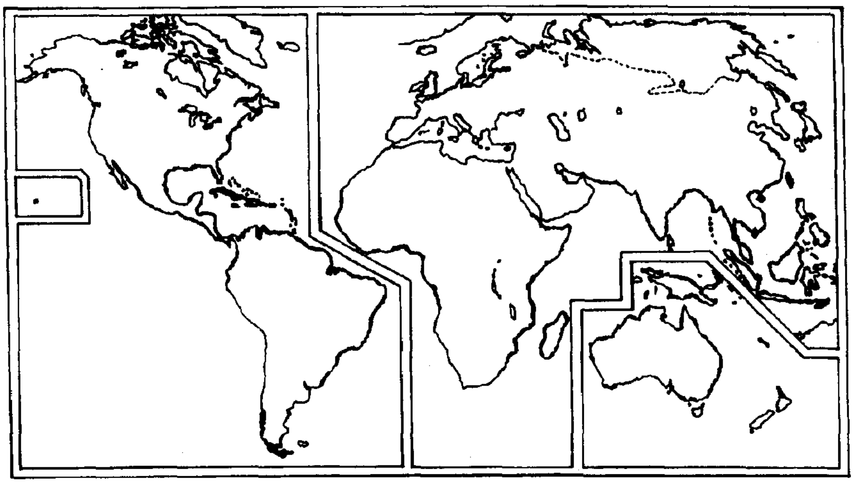

Fig. 1 World Distribution of Acid Sulfate Soils [Kawalec 1972]

mined for long periods of time

The distribution of actual and potential acid sulfate soils in Southeast and East Asia is summarized in Table 1 [*ibid.*]. It should be noted that two-thirds of the total five million hectares is found in Indonesia, Thailand and Vietnam. Moormann [1961] has reported about a million hectares in South Vietnam, Watts [1969] reported 200,000 hectares in West Malaysia, while Pons and Kevie [1969] stated that there were 1.5 million hectares in Thailand. Some presumed potential acid sulfate soils (Sulfaquents) in the tidal marshes are likely in Bangladesh, Burma and India.

relatively close to the sea, where they have formed marine and estuarine deposits. Broadly, they are distributed in:

a) Coastal areas with marine or brackish water influences
b) Freshwater backswamps, formerly brackish
c) Lake bottoms reclaimed by poldering and draining of water, such as in the Netherlands
d) Inland continental environments with inherent pyritic parent rock or where lignite and coal have been

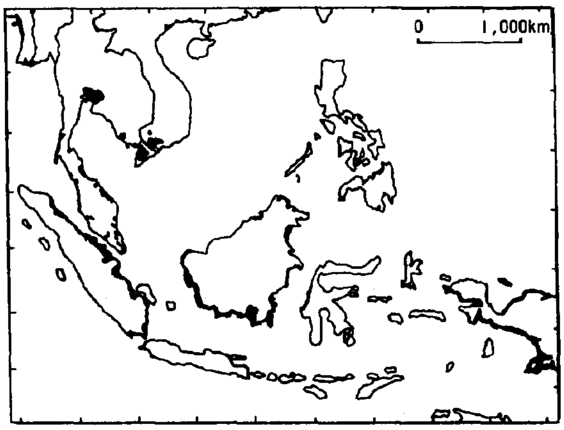

Fig. 2 Major Areas of Acid Sulfate Soils in Southeast Asia [van Breemen and Pons 1978]

In Thailand, about 800,000 hectares of acid sulfate soils are situated in the delta flat of the lower Bangkok Plain. The remainder is scattered along the coastal areas and estuaries of the east coast and the peninsula. The most important acid sulfate soils of the country are those covering 80% of the delta flat, which accounts for 35.6% of total land area of the Bangkok Plain.

The age of the acid sulfate soils on the northern part of the delta flat is 5,000 to 6,000 years, that of those on the southern part about 2,500 to 3,000 years.

Genesis of Acid Sulfate Soils

The formation of acid sulfate soils consists of two main processes: formation

Table 1 Distribution of Acid Sulfate Soils in Southeast and East Asia [van Breemen and Pons 1978]

Country	Area (thousand ha)	Reliability[a]	Soil Classification
Bangladesh			
Chittagong	200[b]	—	Sulfaquents, Sulfaquepts
Khulna Sunderbans	200[b]	—	Sulfaquents
Burma	180[b]	—	Sulfaquents?
China			
Coastal Areas South of Fukien	67	+	Sulfaquepts, Sulfic Haplaquepts
India			
Kerala	110	+	highly organic Sulfaquepts, partly (26,000 ha) affected by salinity
W. Bengal	280[b]	—	Sulfaquents
Indonesia			
Kalimantan and Sumatra	2,000	—	mainly highly organic Sulfaquents and Sulfaquepts and Sulfihemists
Khmer	200	+	mainly Sulfaquepts?
Japan	4	++	Sulfaquepts, Sulfic Haplaquepts
	17	++	potentially acid shallow sea bottom
Malaysia			
W. Malaysia	150	+	highly organic Sulfaquepts and Sulfaquepts, perhaps also Sulfihemists
Sarawak	10	—	mangrove marshes acidified due to lobster mounds
Philippines			
Luzon, Mindanao	7	—	Sulfic Tropaquepts, Sulfaquepts, highly organic Sulfaquepts
South Korea	3	+	Sulfic Haplaquepts, Sulfaquents
Thailand			
Bangkok Plain	600	++	Sulfic Tropaquepts (550,000 ha), Sulfaquents (—10,000 ha), Sulfaquepts (50,000 ha)
Southeast Coast	20	+	Sulfaquepts, Sulfaquents
Peninsula	50	+	Sulfaquepts, partly highly organic
Vietnam			
Mekong Delta	1,000	—	mainly Sulfaquepts (partly highly organic), smaller areas of Sulfic Tropaquepts and highly organic Sulfaquents

a. Reliability of hectarage estimate: —=poor, +=fair, ++=good
b. These figures are probably gross overestimates.

and oxidation of pyrite.

Formation of Pyrite

The accumulation of pyrite is brought about by the combined effect of somewhat unique conditions that occur in tropical coastal areas. The sulfur in pyrite is derived from the sulfate in sea water, which is biologically reduced to sulfide in the anaerobic mud. An energy source is necessary for bacterial sulfate reduction, and organic matter is usually readily available as a result of abundant plant growth in these coastal areas. Also, ferrous iron (Fe^{2+}) must be available, and it is usually derived from the reduction of insoluble ferric compounds that result from the weathering of clay. Thus the combination of sulfate from sea water, organic matter from plant growth, anaerobic conditions caused by exclusion of atmospheric oxygen by the excess water, and the presence of Fe^{2+} result in the formation and accumulation of pyrite in tropical coastal wetlands.

$$Fe_2O_{3(s)} + 4\,SO_4^{2-}{}_{(aq)} + 8\,CH_2O^{1)} + 1/2\,O_{2(g)} \longrightarrow 2\,FeS_{2(s)} + 8\,HCO_3^{-}{}_{(aq)} + 4\,H_2O_{(l)}$$

This overall reactions includes reduction of all sulfate to sulfide, followed by oxidation of sulfide (with Fe (III) and O_2 as oxidants) to disulfide (S_2^{2-}).

Pons *et al.* [1982] proposed that the solid-solid reaction of FeS and S to form FeS_2 is a slow process, which takes months or years to produce measurable quantities of pyrite; but the direct precipitation of Fe^{2+} and S_2^{2-} to form FeS_2 yields pyrite within days under favorable conditions [Goldhaber and Kaplan 1974].

Oxidation of Pyrite

The fine-grained pyrite typical of tidal sediments is readily oxidized upon exposure to air, giving Fe (II) sulfate and sulfuric acid:

$$FeS_2 + 7/2\,O_2 + H_2O \longrightarrow Fe^{2+} + 2SO_4^{2-} + 2\,H^+$$

Complete oxidation and hydrolysis of iron to Fe (III) oxide yields 2 moles of sulfuric acid per mole of pyrite:

$$FeS_2 + 15/4\,O_2 + 7/2\,H_2O \longrightarrow Fe(OH)_3 + 2\,SO_4^{2-} + 4\,H^+$$

[van Breemen 1982].

Pyrite is oxidized more rapidly by dissolved Fe (III) than by oxygen, according to

$$FeS_2 + 14\,Fe^{3+} + 8\,H_2O \longrightarrow 15\,Fe^{2+} + 16\,H^+ + 2\,SO_4^{2-}$$

Oxidation Products

Most of the iron (II), hydrogen, and sulfate ions released during pyrite oxidation further undergo various reactions in the soil. The followings are some of the important oxidation products.

Jarosite

Jarosite is formed only in acid (pH 2 to 4), oxidized (Eh>400 mv) environments. The pale yellow (2.5–5 Y 8/3–8/6) jarosite ($KFe_3(SO_4)_2(OH)_6$) is conspicuous in most acid sulfate soils. It commonly occurs as earthy fillings of void or as mottles in the soil matrix, and invariably gives a sharp X-ray diffraction pattern. In acid sulfate soils, the jarosite is metastable and will eventually be hydrolyzed to goethite [*ibid.*]. The pale yellow mottles are so characteristic that they are used, together with pH, as a diagnostic criterion for classifying acid sulfate soils [USDA 1975]. However, jarosite is lacking in some acid sulfate soils, particularly those high in organic matter [Kosaka 1971].

Iron Oxides

Most of the iron from oxidized pyrite ends up as Fe (III) oxides. Fine-grained goethite may form either directly, and

1) CH_2O stands for organic matter.

quickly, upon oxidation of dissoved Fe (II) sulfate released during pyrite oxidation, or more slowly, by hydrolysis of jarosite:

$$Fe^{2+}+SO_4^{2-}+1/4\,O_2+3/2\,H_2O \longrightarrow FeOOH+2\,H^++SO_4^{2-}$$

$$\text{Jarosite} \longrightarrow 3\,FeOOH+2\,SO_4^{2-}+K^++3\,H^+$$

In the better drained, deeply developed acid sulfate soils, part of the Fe (III) oxides in the B horizon may occur as hematite, giving conspicuous red mottles.

Gypsum

If the soils contain an appreciable amount of a neutralizing compound such as $CaCO_3$, the precipitation reaction could occur:

$$2\,CaCO_3+K\,Fe_3(SO_4)_2(OH)_6+5\,H_2O+H^+ \longrightarrow 2\,CaSO_4\cdot 2H_2O+3\,Fe(OH)_3+K^++2\,CO_2$$

The formation of gypsum in acid sulfate soils is an indication of the soils being relatively suitable for agriculture.

Classification

Nomenclature related to classification of acid sulfate soils is as follows.

Sulfuric Horizon

This consists of mineral, organic or mixed soil material, generally containing yellow jarosite mottles with hue 2.5 Y or yellower and chroma 6 or more, which has a pH$\leqslant$3.5 (1 : 1 in water) and contains at least 0.05% water soluble sulfate.

In practice, the pH criterion alone suffices, because there are very few soils with a pH (in water) below 3.5 which are not influenced by sulfuric acid.

Sulfidic Material

This is waterlogged mineral, organic, or mixed soil material with a pH of 3.5 or higher, containing oxidizable sulfur compounds, which, if incubated as a 1-cm thick layer under moist, aerobic conditions (field capacity) at room temperature, shows a drop in pH of at least 0.5 unit to a pH below 3.5 within four weeks.

Acid sulfate soils can be classified as Sulfaquepts (Aquepts with a sulfuric horizon that has its upper boundary within 50 cm of the soil surface), Sulfic Tropaquepts (Tropaquepts with jarosite mottles and a pH 3.5 to 4 somewhere within the 50 cm depth, or with jarosite mottles and a pH$<$4 in some part between 50 to 150 cm depth), or Sulfic Haplaquepts (comparable to Sulfic Tropaquepts but formed under a more temperate climate). The distinction between Sulfaquepts and Sulfic Tropaquepts is very useful agronomically in that the former are generally unsuitable for agriculture without costly amendment measures, whereas the latter can often be made productive easily.

Potential acid sulfate soils are either Sulfaquents (Aquents with sulfidic material within 50 cm of the mineral soil surface), Sulfic Fluvaquents (Fluvaquents with sulfidic material between 50 and 100 cm depth), or Sulfihemists (Histosols with sulfidic material within 100 cm depth).

Para or pseudo acid sulfate soils can be classified as Tropaquepts or Haplaquepts.

Acid sulfate soils that are dominantly organic may be Sulfohemists (Histosols with a sulfuric horizon that has its upper boundary within 50 cm of the surface) [van

Breemen 1982].

Suitability of Acid Sulfate Soils for Growing Rice

Work on land capability classification by the Department of Land Development [Kevie and Yenmanas 1972] separated the classification of lowland from that of upland and established five soil suitability grouping for growing rice, ranging from group P I for soils very well suited for paddy land, to group P V for soils generally not suited for paddy land. Within each suitability group there are subgroups defined by various limitations, which are designated by the following symbols: m, lack of moisture for plant growth; t, unfavorable topography; and a, soil acidity. Thus, for example, P IIa indicates that soils are well suited for paddy with moderate soil acidity causing slight limitation for rice production. P IIIa indicates that soils are moderately suited for paddy with severe acidity restricting rice production. P IVa soils are poorly suited for paddy, with very severe acidity restricting rice production. According to Kevie and Yenmanas [*ibid.*], all of the acid sulfate soils of the Central Plain were classified as suited for paddy within these three subgroups, i.e., P IIa to P IVa. None of the acid sulfate soils were recognized to be P I, which is very well suited for paddy land and normally belongs to the fertile river alluvial paddy soil, namely, the Ratchaburi series, or to non-acid marine soil, such as the Bangkok series.

Total area of acid sulfate soils in each suitability class, their major soil series and percentage share of the total area of acid sulfate soils in the Central Plain of Thailand are shown in Table 2. According to Kevie and Yenmanas [*ibid.*], the production capacity of the P IIa soils, without any fertilization, would be 1.2–2.2 t/ha of paddy. Rice will respond slightly to lime and fertilizer. The main acid sulfate soil in this group is Sena, which accounts for about 49.8% of the total area of P IIa. The P IIIa, due to its severe acidity restriction of rice production, would have a paddy production capacity of 0.9–1.6 t/ha without liming and fertilization. The rice will respond only slightly to fertilizer without liming. The main soil series in this group is Rangsit, which accounts for 82% of the total area of the P IIIa. P IVa is of extremely limited suitability for rice production due to its very severe soil acidity, and some areas are left uncultivated. The cultivatable areas give paddy yields of less than 0.9 t/ha, normally between 0.3–0.6 t/ha. To increase the paddy yield by 50%, the application of 30–45 kg N, 37 kg P_2O_5 together with 3–6 tons of lime per hectare would be required. The most important soil in this group is the Rangsit very acid phase, which covers about 70.8% of the total area of the P IVa.

The main criterion used to determine the extent of limitation due to soil acidity of acid sulfate soils for paddy is the depth of the jarositic horizon. Jarosite, a basic iron potassium sulfate, is produced within the soil profile by the action of sulfuric acid on aluminosilicate minerals and is found in an acidic horizon having pH 3.65–

Table 2 Soil Suitability Classification and Area of Acid Sulfate Soils in the Central Plain, Thailand (Modified from Kevie and Yenmanas [1972])

Soil Series	pH	Area (ha)	% of Total Area	% of Class Total	Soil Suitability Class
1. Maha Phot (Ma)	4.5-5.5	62,664	10.6	21.1	P IIa: Soil well suited for paddy with moderate limitation due to soil acidity, average yield 1.2–2.2 t/ha
2. Ayutthaya (Ay)	4.5-7.0	78,205	13.3	26.4	
3. Ay/Ma	4.4-7.0	7,475	1.3	2.5	
4. Sena (Se)	4.5-5.0	147,814	25.1	49.8	
5. Thakhwang	4.5-5.0	419	—	0.2	
Total of P IIa		296,577	50.3	100	
6. Se/Rs	4.5-5.0	13,062	2.2	5.8	P IIIa: Soil moderately suited for paddy with some limitation due to soil acidity, average yield 0.9–1.6 t/ha
7. Rangsit (Rs)	4.5-5.0	180,222	30.6	82.0	
8. Rangsit (High Phase)	4.5-5.0	168	—	0.2	
9. Thanyaburi	4.5-5.0	26,518	4.5	12.0	
Total of P IIIa		219,970	37.3	100	
10. Rangsit Very Acid Phase (RVAP)	3.5-4.5	51,240	8.7	70.8	P IVa: Soil poorly suited for paddy with severe limitation due to soil acidity, average yield 0.9 t/ha
11. Ongkharak	4.0-4.5	12,323	2.1	17.0	
12. Cha-am	3.0-4.4	8,811	1.5	12.2	
Total of P IVa		72,374	12.3	100	
Total		588,921	100	—	

3.5 or less. The nearer jarosite is to the surface, the more likely it will be to affect the acidity of the surface layers due to the rising groundwater at the start of the rainy season bringing acid from this layer to the surface. The relationship between the depth of jarositic horizon and suitability class is as follows:

Jarositic horizon within 40 cm; Suitability class P IVa

Jarositic horizon between 40–100 cm; Suitability class P IIIa

Jarositic horizon below 100 cm; Suitability class P IIa

A recent survey by Osborne [1984] explored chemical parameters within 1 m of the soil surface that might be used as more reliable criteria for the acidity classification of acid sulfate soils. These parameters are bases, aluminum, sulfates and pyrite. The ranges of each parameter assigned to different soil acidity classes and the new provisional soil acidity class maps have been proposed [*ibid.*]. According to this proposal, there are five acidity classes:

Class I neutral to slightly acid
—lime not required

Class II slightly acid
—probably no economic response to lime

Class III moderately acid
—likely respond to lime (marl)

Class IV severely acid
—marl essential at 6–10 t/ha

Table 3 Parameters Used for Assignment to Acidity Classes with Value for Each Class [Osborne 1984]

Parameters \ Acidity Class	Values Used for Assignment				
	I	II	III	IV	V
Extr. Aluminum					
(me/100 g Soil)	<1	1.0-5.0	5.1-9.0	9.1-13.0	>13
% Al Saturation (Al/Al+Bases)	0-5.0	5.1-25.0	25.1-45.0	45.1-65.0	>65
% Base Saturation	>65	50.1-65.0	35.1-50.0	20.0-35.0	<20
Extr. Calcium					
(me/100 g Soil)					
0–20 cm	>12.4	7.5-12.4	2.5-7.4	1.0-2.4	<1
0–40 cm	>10	6.5-10.0	3.0-6.4	1.0-2.9	<1
Total Sulfur %	<0.05	0.050-0.100	0.101-0.240	0.241-0.400	>0.4
Acid Extr. S—Amm. Acetate Extr.					
(me/100 g Soil)					
0–40 cm	<−5	−5.0 to 2.5	2.6-10.0	10.1-20.0	>20
40–100 cm	<+5	5.0-15.0	15.1-25.0	25.1-35.0	>35

Class V extremely acid
—marl essential at 10–15 t/ha

The parameters used and the ranges assigned for each acidity class are shown in Table 3.

Class I includes recent alluvial soils; some low terrace soils and soils from recent marine clay similar to those of the former soil suitability classification (Bangkok and Ratchaburi series).

Class II includes some low terrace soils; soil on former tidal flats where pyrite has been oxidized to a greater depth and the oxidation products leached below 1 m or neutralized as calcium sulfate. The acidity class II covers a wider acreage of acid sulfate soils than the former P IIa, due to its inclusion of most of Don Muang and parts of the Rangsit and Thanyaburi series formerly belonging to P IIIa.

Class III includes soils on former tidal flats with older brackish water deposits where oxidation products remain within 1 m depth. It covers mainly the major part of Rangsit, and parts of the Don Muang and Thanyaburi series. This proposed acidity class III covers a much smaller area than P IIIa, 1,395 to 1,705 km² as compared to 2,200 km² or only 63–77% [McWilliam 1984].

Classes IV and V include soils on former tidal flats with older brackish water deposits which are low in bases. These include similar main soil series to P IVa (Ongkharak and Rangsit very acid phase), but cover a smaller land area than P IVa: 444 to 559 km² as compared to 636 km², or 70–88% [*ibid.*]. From this proposed provisional soil acidity classification, it was suggested that acreages of extremely acid soils which needed to be improved by liming for the rice crop to respond satisfactorily to fertilization amounted to only 57.7% of the area originally envisaged from the soil

Table 4 Comparison of Areas of Acid Sulfate Soils of P IIa, P IIIa and P IVa [Kevie and Yenmanas 1972] and of Soil Acidity Classification [Osborne 1984]

Soil Series	Kevie and Yenmanas		Acidity Class	Osborne	
				Area (km^2)	
	Class	Area (km^2)		0–20 cm	0–40 cm
Rangsit+Thanyaburi+ 1/2 (Sena/Rangsit)	P II & IIIa	2,200	III	1,395	1,705
Rangsit Very Acid Phase+ Ongkharak	P IVa	636	IV	444	559
Total		2,836		1,839	2,264
Acid Units Included in the Liming Project of DLD		2,774			
Area Proposed for Improvement by Osborne		1,600 (57.7% of DLD)		1,061	1,306

Adopted from Appendix III: Schedule B of McWilliam [1984].

suitability classification based on mapping units (1,600 km^2 rather than 2,774 km^2) (Table 4). However, there are approximately 1,000 km^2 less of acid soils likely to respond to marl application on the basis of soil chemical parameters at 0–20 cm [*ibid.*; Osborne 1984].

Assuming this figure is valid, according to Osborne [1984], a maximum of approximately 1,300 km^2 is likely to respond to improvement including marl application. To ameliorate these soils, if marl applications per hectare were made at 9.4 cubic meters and 6.2 cubic meters for class IV (extremely acid) and class III (severely acid) soils respectively, at least about 740,000 cubic meters of marl would be required. To confirm the validity of this assessment, starting with the 1984 season, test blocks are being laid down at various sites to evaluate marl application at various rates at two levels of N–P fertilization. If the 0–20 cm map proves to be correct, then there are 1,000 km^2 less of the severely and extremely acid soils which truely need lime in the eastern portion of the Bangkok Plain of Thailand than is indicated by the soil suitability classification based on mapping units.

Chemical and Fertility Characteristics

The chemical characteristics and available nutrients of representative acid sulfate soils of suitability class P IIa, P IIIa and P IVa are compared with those of recent alluvial and marine clay of class P I in Table 5 and Table 6. Rangsit very acid phase (RVAP), representing soil suitability class P IVa, has a pH of the surface soil of 3.9, which is extremely acidic. Rangsit (Rs) and Sena (Se), representing soils of class P IIIa and P IIa respectively, have pHs of 4.8 and 4.7, which are strongly acidic. Bangkok (Bk) and Ratchaburi (Rb), representing soils of class P I, have pHs of 5.2 and 5.8, which

Table 5 Chemical and Available Nutrient Characteristics of Surface Soils [Attanandana *et al.* 1981]

	Method*	P I Ratchaburi	P I Bangkok	P IIa Sena	P IIIa Rangsit	P IVa RVAP
		(Fresh Water Alluvium)	(Non-acid Marine)	Brackish Water Alluvium		
pH		5.8	5.2	4.7	4.8	3.9
Organic Matter (%)	1	1.5	1.3	2.2	2.1	3.1
P (ppm)	2	50.8	23.6	9.6	10.5	6.1
K (me/100 g)	3	0.16	0.67	0.42	0.37	0.17
Na (me/100 g)	3	0.76	2.70	0.60	1.20	3.70
Ca (me/100 g)	3	7.5	10.0	13.1	10.0	2.5
Mg (me/100 g)	3	2.7	9.3	4.0	8.5	5.6
Al (me/100 g)	4	0.09	0.18	0.55	0.81	11.4
CEC (me/100 g)	5	17.6	23.2	31.2	26.4	30.6
Si (mg SiO_2/100 g)	6	11.4	14.1	10.1	10.9	3.6
SO_4 (ppm S)	7	0	520	440	176	400
Fe (ppm)	8	305	170	200	220	50
Mn (ppm)	8	58	30	60	39	15
Cu (ppm)	8	2.2	1.7	2.5	1.5	0.1
Zn (ppm)	8	3.0	2.5	2.5	2.5	2.5

* 1 Walkley-Black method
2 Bray II
3 Exchangeable cations by 1N NH_4OAc pH 7.0
4 Extractable by 1N KCl
5 By N NH_4OAc pH 7.0
6 Extractable by 1N CH_3COOH pH 4.0
7 Water soluble [van Breemen 1971]
8 Extractable by 0.005 M DTPA pH 7.30

are moderately and weakly acidic respectively. Compared with normal soil (P I soils), the organic matter content of the acid sulfate soils are generally much higher; and among the acid sulfate soils, the content of organic matter tend to be higher, the lower the pH of the surface soil. This is because low pH is unfavorable for organic matter decomposition and retards the ammonification, regardless of the high organic matter content. From Table 7 the RVAP contains 6.4% organic matter, which is the

Table 6 Clay Mineral Composition and Content of Selected Elements of Surface Soils [Attanandana *et al.* 1981]

Soil Series	Clay Mineral Composition in % 7 Å Clay	10 Å Clay	14 Å Clay	CaO (%)	S (ppm)
Ratchaburi (Rb)	50	25	25	0.5	181
Bangkok (Bk)	25	20	55	0.4	1,131
Sena (Se)	55	15	30	0.6	1,281
Rangsit (Rs)	50	10	40	0.4	706
Rangsit Very Acid Phase (RVAP)	65	10	25	0.05	5,235

highest among all the soils, but its ammonification percentage is only 0.5 as compared to 1.5 and 2.2 of the Rs and Se, respectively. Therefore, rice growing in the acid sulfate soils will respond to nitrogen fertilizer regardless of their organic matter content. Liming the RVAP will hasten the mineralization and promote a higher response of the growing crop to the added nitrogen. Since the RVAP is very low in available phosphorus, liming have to be accompanied by sufficient phosphate fertilization to produce striking effect [Attanandana *et al.* 1981]. In fact, high doses of phosphate fertilization alone can raise the rice yield to a certain extent, and in combination with liming, even higher yields will be obtained [Uwaniyom and Charoenchamratcheep 1984].

Table 7 The pH, Organic Matter Content and Ammonification Percentage of Acid Sulfate and Non-acid Sulfate Soils

Soil Series	pH	% O.M.	Total N	Ammonification Percentage
Ratchaburi (Rb)	6.0	1.7	0.08	3.5
Bangkok (Bk)	4.5	3.4	0.17	1.7
Sena (Se)	4.5	3.7	0.19	2.2
Rangsit (Rs)	4.1	2.0	0.10	1.5
Rangsit Very Acid Phase (RVAP)	4.0	6.4	0.32	0.5

It should be noted that the top soil samples of Sena and Rangsit soils showed no significant differences in pH or analysis of nutrients and therefore the difference between them in suitability rating for paddy production is not reflected by the inherent properties of their top soils. It was suggested that other factors related to the interactions between top soil and subsoil and/or the water regime of the soils result in dynamic processes with unfavorable effects on plant performance [Attanandana *et al.* 1981].

The extremely acid RVAP soil has the lowest figures for available P (6.1 ppm) and extractable Si (3.6 mg SiO_2/100 g). Extractable K, Ca, Fe and Cu are also low, while extractable Al (11.4 me/100 g) is exceedingly high. These inherent properties of RVAP topsoil together with its pH of 3.9 indicate a low fertility status and a potential for release of soluble Al in toxic amounts upon flooding. In contrast to the P IIa and P IIIa soils (Se and Rs), the low productivity rating of the P IVa soils is considered to be due to the inherent properties of the top soil and most probably of the soil body in its totality [*ibid.*]. Among the acid sulfate soils, the RVAP contains the lowest CaO (0.05%) and the highest S (5,235 ppm) contents. Mineralogically, it also contains the highest proportion of 7 Å clay minerals and the lowest of 14 Å clay minerals (Table 6).

Fertility Problems of Acid Sulfate Soils

Acid sulfate soils are generally unproductive. Their low productivity may be due to one or more of the following unfavorable factors: soil acidity, salinity, aluminum toxicity, iron toxicity, low content of major nutrients, low base status, and hydrogen sulfide toxicity.

1. Soil Acidity

The reported ills of acid sulfate soils may be due to the direct effect of hydrogen ions, especially below pH 3.5 to 4. However, aluminum toxicity is probably more important in this pH range.

2. Salinity

Acid sulfate soils in tidal areas are often affected by salinity. Salinity aggravates other toxicities, both by weakening the plants and by increasing iron and perhaps aluminum in solution [Parischa and Ponnamperuma 1976]. Moreover, in many young acid sulfate soils, tidal electrolyte content increases greatly upon soil reduction and reaches harmful levels [Ponnamperuma *et al.* 1972].

3. Aluminum Toxicity

One cause of stress on the growth of certain plant species is aluminum toxicity. A high Al level affects cell division, disrupts certain enzyme systems, and hampers uptake of phosphorus, calcium and potassium [Rorison 1972].

Most plants grown on acid sulfate soils which have a pH below 4 suffer from Al toxicity. The death of rice plants grown in soil from Vietnam was attributed to Al toxicity (68 ppm in soil solution).

4. Iron Toxicity

Dissolved iron in excess of 300–400 ppm is toxic to rice [Ponnamperuma *et al.* 1955]. Nhung and Ponnamperuma [1966] reported that the concentration of Fe^{2+} in a Vietnamese soil reached 800 ppm after six weeks of submergence. In a later study, 5,000 ppm of water-soluble Fe was found two weeks after submergence in an acid sulfate soil [Ponnamperuma *et al.* 1972]. Tanaka and Navasero [1966] found from 500 to 700 ppm of Fe in solutions obtained from two Malaysian and Vietnamese acid sulfate soils after 30 days of incubation.

5. Low Nutrient Content

In the absence of iron and aluminum toxicity and harmful salinity, phosphorus deficiency is the most important problem of acid sulfate soils, especially the Sulfic Tropaquepts of the Bangkok Plain. Supply of nitrogen increases the phosphate response [Attanandana *et al.* 1981: Table 11].

6. Low Base Status

During the formation of acid sulfate soils, bases are removed as sulfate and most of the exchange complex is occupied by aluminum. Therefore, acid sulfate soils are likely to be deficient in Ca and K. Exchangeable Ca content of 3.5–5.0 me/100 gm and exchangeable Mg of 3.0–3.2 me/100 gm in the top 35 cm of an acid sulfate soil in Thailand has been reported [Sombatpanit 1970]. Andriesse *et al.* [1972] showed that the soils from lobster mounds had the highest exchangeable Ca value of 1.6 me/100 gm. Pham *et al.* [1961] reported 3.0, 2.9 and 3.6 me/100 gm of exchangeable Ca for the 0–35 cm, the cat clay horizon and the reduced horizon; the corresponding figures for magnesium were 4.1, 5.7 and 9.0 me/100 gm, reflecting the brackish (or marine) origin of the soil.

7. Hydrogen Sulfide Toxicity

Hydrogen sulfide has been shown to be toxic to the rice plant through its suppression of the oxidizing power of the roots [Vamos 1967]. The work of Moraghan and Patrick [1974] showed that sulfate reduction occurred slowly at pH 5 and increased as the pH was increased from 5 to 7. van Breemen [1975] showed that when the pH increases above 4.5 to 5, sulfate reduction takes place, producing sulfide which is then precipitated as FeS. If the soil is low in Fe^{2+}, H_2S toxicity might be possible. The work of Attanandana *et al.* [1985] on potential acid sulfate soil indicated that acid-soluble sulfide was detected at Eh of −55 mv or equivalent to Eh_7 of −103 mv and the soil pH was 6.2. The condition of pH 6.2 could arise from liming of this acid sulfate soil. However, this soil normally contains quite high amount of active Fe, so that free sulfide is not found.

Another experiment using a sample of Rangsit very acid soil limed to various pH levels showed that acid-soluble sulfide was highest with the soil pH of 7.7. Soil with pH 5.2 showed markedly lower content of acid-soluble sulfide.

Free sulfide was detected at Eh of −105 mv (pH 5.2), −215 mv (pH 6.2) and −285 mv (pH 7.7) in concentrations of 0.16, 0.24 and 0.15 μg S/ml, respectively (Table 8). This soil was low in active Fe (0.3%), so that the iron was not sufficient to inactivate the free sulfide.

Table 8 Acid-soluble Sulfide and Free Sulfide Detected in Rangsit Very Acid Soil on Different Liming Treatments

Treatment	Eh (mv)	Acid-soluble Sulfide (μg/ml)	Free Sulfide (μg/ml)
Control	+25	—	—
Limed to pH 5.2	−105	2.1	0.16
Limed to pH 6.2	−215	18.4	0.24
Limed to pH 7.7	−285	28.0	0.15

Amelioration

Millions of hectares of acid sulfate soils in South and Southeast Asia lie idle or are cultivated with poor results largely because of strong acidity. If these lands can be improved for rice cultivation, the food deficits expected in South and Southeast Asia in the future may be reduced. Acid sulfate soils are among the major problem soils and require appropriate methods of amelioration. Since the soils are lowland and suitable for rice culture, amelioration measures for wetland rice include:

1. Leaching and drainage
2. Submergence
3. Liming
4. Manganese dioxide addition
5. Nitrogen, phosphorus and potassium application including utilization of rock phosphate as phosphate source
6. Use of resistant varieties

Amelioration of Acid Sulfate Soils:

1. Leaching and Drainage

1.1 Leaching

The accumulation of soluble salts and aluminum when acid sulfate soils are submerged can sometimes reach toxic levels. Removal of these substances is therefore necessary and can be accomplished by leaching.

Table 9 Influence of Leaching and Liming on the Yield of Rice on Two Flooded Acid Sulfate Soils [Ponnamperuma *et al.* 1972]

Treatment	Yield (g/pot)			
	Soil from Vietnam		Soil from the Philippines	
	Grain	Straw	Grain	Straw
Control	21	24	0	0
Limed to pH 5.5	64	64	79	76
Leached	78	75	11	20
Leached+Limed	88	78	83	82

Table 9 shows the beneficial effect of leaching on the rice yield on two flooded acid sulfate soils. One was a soil from Vietnam, the other an acid sulfate soil from the Philippines. Leaching of the soils depressed specific conductance and the sulfate contents, increased pH slightly, and lowered the concentration of water-soluble iron and the partial pressure of CO_2. These effects were pronounced in the soil from Vietnam, but less so in soil from the Philippines. Leaching reduced the concentration of Al in the soil solution from 69 ppm to 0.6 ppm in soil from Vietnam and from 106 ppm to 11 ppm in soil from the Philippines at the start of the experiment. Leaching alone gave the best straw and grain yield in soil from Vietnam but was not a satisfactory amendment in soil from the Philippines. The failure of leaching alone in soil from the Philippines was due to the build up and persistence of a high concentration of Fe^{2+}. In practice, however, leaching is not normally possible due to the impermeability of the soil and the low elevation of the land. Table 10 shows the ineffectiveness of leaching under field conditions.

1.2 Drainage

A shallow drainage system is currently being used by Vietnamese farmers. First, an intensive network of shallow ditches is dug. As the ditches are excavated, the land between two ditches becomes a slightly raised bed on which rice is grown. Rice yields usually double in the first year and from the second year on, a yield increase of two to four times is reported by most farmers [Xuan *et al.* 1981].

2. *Submergence*

When an acid soil is flooded, the pH rises [Hesse 1961; IRRI 1963] and if kept submerged until the pH increases sufficiently, aluminum toxicity is eliminated and iron toxicity minimized [Ponnamperuma

Table 10 Effects of Presubmergence, Leaching and Liming on the Grain Yield on Thanyaburi Soil [Attanandana 1982]

Wet Season 1972	Wet Season 1973	Dry Season 1974	Average of 3 Years	Percent Increase
	Grain Yield (kg/ha)			
		Presubmergence (*A*)		
A_0 4,181 a	4,888 a	5,269 a	4,775	7.7
A_1 4,875 b	5,238 b	5,313 a	5,144	
		Leaching (*B*)		
B_0 4,481 a	5,063 a	5,281 a		
B_1 4,456 a	5,063 a	5,300 a		
		Liming (*C*)		
C_0 4,244 a	4,919 a	4,913 a	4,694	11.5
C_1 4,813 b	5,213 b	5,669 b	5,231	

Any two means followed by the same letter are not significantly different at the 5% level.

1964] permitting rice to grow normally. Attanandana [1982] showed that grain yields were increased by 7.7% for three successive years in a field experiment on an acid sulfate soil in Thailand by means of presubmergence for six weeks before planting (Table 10).

3. *Liming*

Several researchers have reported liming to be the simplest way of increasing the pH of the soil. Table 9 shows the beneficial effect of liming on acid sulfate soils from Vietnam and the Philippines. The combination of leaching and liming had the greatest effect. Table 11 also shows the beneficial effect of liming on Rangsit very acid soil. Dry matter increased at every level of fertilization. The effect was pronounced at the P_1 level. The beneficial effect of liming was clear, dry matter weight was higher in the Rangsit very acid+lime than in Rangsit very acid at every level of fertilization. The average effect of liming was an increase in dry matter weight in the range of 35–44%. Another important effect of liming is the increased availability of most plant nutrients. Table 12 reveals that P, K, Ca, Mg increased while Na, S, Al, Fe in the plant decreased due to liming.

Table 11 Average Yield Responses (g dry matter /pot) to Application of N, P and K on Rangsit Very Acid and Rangsit Very Acid+Lime Soil [Attanandana *et al.* 1981]

Level of Nutrient	Soil: Rangsit Very Acid (g/pot)	Soil: Rangsit Very Acid+Lime (g/pot)	% due to Lime
ppm N/pot			
N_0 (0)	24.0	29.3	22
N_1 (250)	64.9	88.1	36
N_2 (500)	84.4	123.9	47
N_3 (750)	78.4	125.6	60
LSD .05	17.8	15.3	av. 40%
.01	23.8	20.5	
ppm P_2O_5/pot			
P_0 (0)	1.7	2.2	29
P_1 (100)	62.7	104.9	67
P_2 (200)	77.8	122.1	57
P_3 (400)	110.0	136.3	24
LSD .05	17.8	15.3	av. 44%
.01	23.8	20.3	
ppm K_2O/pot			
K_0 (0)	82.6	109.7	33
K_1 (120)	129.5	192.6	49
K_2 (240)	142.5	207.2	45
K_3 (360)	159.1	181.4	14
LSD .05	35.6	30.7	av. 35%
.01	47.7	41.7	

4. *MnO_2 Addition*

Because of the high standard oxidation-reduction potential of the MnO_2–Mn^{2+}

Table 12 Concentration of Plant Nutrients of Rice Grown on Two Soils (Average of Fertilized Plots) at Booting Stage [Attanandana *et al.* 1981]

Soils	P (%)	K (%)	Ca (%)	Mg (%)	Na (%)	S (%)	Si (%)	Al (ppm)	Fe (ppm)	Dry Weight (g/pot)
Rangsit Very Acid	0.18	1.25	0.43	0.33	1.00	0.76	2.1	255	215	73
Rangsit Very Acid+Lime	0.22	1.85	0.70	0.42	0.53	0.49	2.2	133	152	91

system, soil reduction is retarded by MnO_2 addition. Manganese dioxide improved the growth and yield of rice in an acid sulfate soil because it depresses the concentration of water-soluble Fe^{2+} and Al^{3+}. The effect of MnO_2 of decreasing Fe^{2+} in the soil solution was clearly shown in a series of experiments by Nhung and Ponnamperuma [1966].

Their results showed that manganese dioxide at 1.0% by weight of the soil caused (a) slight increase in pH of the soil solution, (b) depression of the concentration of Al^{3+}, Fe^{2+} in the soil solution, (c) marked increase of the concentration of manganese in the soil solution and (d) apparent retarding of SO_4^{2-} reduction.

Because of these benefits, manganese dioxide improved the growth and yield of rice, especially in the presence of 0.4% $CaCO_3$. Manganese dioxide produced no additional significant effect in the presence of 0.8% $CaCO_3$ because $CaCO_3$ at this level alone had eliminated Al and Fe toxicities.

The work of Solivas and Ponnamperuma [1982] has also shown that MnO_2 addition increases the grain yield of rice.

5. *Nitrogen, Phosphorus and Potassium*

Some acid sulfate soils present less problem with iron and aluminum toxicities but are well known for their severe deficiency of nitrogen and phosphorus. Application of 50 kg/ha P_2O_5 markedly increased the grain yield of rice at all pH levels studied, although at pH 4.5 the difference was not significant [Khouma and Touré 1981].

The direct and residual effects of rock phosphate application on the acid sulfate soils of Vietnam is shown in Table 13.

The data in Table 13 demonstrate that Lao Cai phosphate alone had no significant effect in the first season, but its residual effect increased rice yields by 62% in the second year. In the absence of phosphate, nitrogen+potassium fertilizer also had no effect in the first season, and only a small positive effect in the second season. Both the immediate and the residual effect of phosphate was greatly increased by applying nitrogen and potassium.

Application of rock phosphate to Rangsit very acid would be advantageous due to its low cost and high availability under acid conditions.

The combination of lime and rock phosphate is important. Application of rock phosphate with a certain rate of lime

Table 13 Direct and Residual Effects of High-grade Lao Cai Rock Phosphate with and without N+K on Rice Yield in Acid Sulfate Soil at An Lac Experiment Station [Le van Can 1981]

Treatment	First Season		Second Season		Combined Effect per 100 kg of Phosphate Rock (kg paddy)
	Paddy Yield (t/ha)	Immediate Effect (t/ha)	Paddy Yield (t/ha)	Residual Effect (t/ha)	
1. Control	1.57	—	0.87	—	
2. Phosphate 600 kg/ha	1.60	0.03	1.41	0.54	95
3. N 60 K 30	1.48	—	1.08	—	
4. N 60 K 30+ Phosphate 600 kg/ha	2.82	1.34	1.91	0.83	361
LSD 0.05	0.12		0.18		

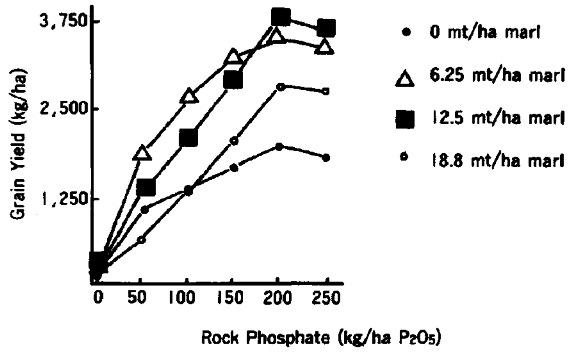

Fig. 3 Effects of Rock Phosphate and Marl on the Grain Yield of Rice on Rangsit Very Acid Soil

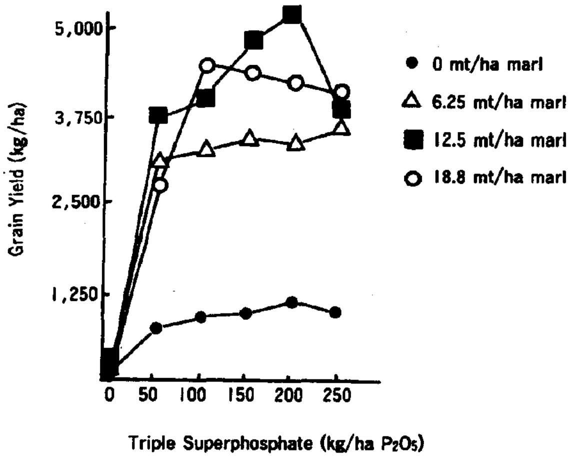

Fig. 4 Effects of Triple Superphosphate and Marl on the Grain Yield of Rice on Rangsit Very Acid Soil

Source: Fig. 3 and Fig. 4 are modified from leaflets of Land Development Department, Thailand

(6 t/ha) increased its efficiency, while the application of lime at very high rates reduces its availability (Fig. 3). In the case of triple superphosphate application, the higher rate of lime showed more beneficial effects (Fig. 4).

This experiment also showed that the availability of phosphate was better in the rock than in triple superphosphate under acid conditions (Fig. 3 and Fig. 4).

The residual availability of rock phosphate applied to acid sulfate soils was equally as effective as that of the triple superphosphate, especially in Rangsit very acid soil when used at the same rate of total P_2O_5 content (Table 14).

Another experiment with three different Thai acid sulfate soils revealed that phosphorus application markedly increased the dry weight of rice in all soils when nitrogen and potassium were applied (Table 15). However, a higher level of phosphorus gave only a slight increase in the dry weight. A clear response to potassium was seen only when nitrogen and phosphorus were applied. Dry weight increased little when a higher level of potassium was applied.

6. *Use of Resistant Varieties*

Iron toxicity is a widespread nutritional disorder of wetland rice associated with excess water-soluble iron [Ponnamperuma *et al.* 1955]. In acid sulfate soils, iron toxicity is an important growth-limiting

Table 14 Grain Yield of Rice Grown in a Pot Experiment with Various Soil and Rock Phosphate and Triple Superphosphate Application for Four Successive Crops (gm/pot) [Attanandana and Vacharotayan 1983]

	Immediate Effect			Residual Effect		
	Crop 1			Mean of 3 Successive Crops		
	RP	TSP	% of TSP	RP	TSP	% of TSP
Sena	8.3	62.3	13.3	32.1	38.4	83.6
Rangsit	8.6	47.9	18.0	19.8	30.7	64.5
Rangsit V.A	19.7	48.0	41.0	42.2	40.6	103.9
Bangkok	10.2	56.0	18.2	30.0	24.4	123.0
Ratchaburi	35.5	64.1	55.4	28.9	28.2	102.5
Rangsit V.A +Lime	12.9	52.3	24.7	12.1	30.8	39.3

Table 15 Means of Dry Weight of Rice Plants on Sena, Rangsit and Rangsit Very Acid Soil (gm/pot) (Modified from Attanandana [1982])

Treatment	Sena	Rangsit	Rangsit Very Acid
$N_0P_3K_2$	35.6	24.6	33.4
$N_1P_0K_2$	79.2	150.1	1.7
$N_1P_1K_2$	188.5	168.3	73.0
$N_1P_3K_2$	170.6	151.7	100.9
$N_3P_3K_0$	184.5	143.2	82.6
$N_3P_3K_1$	249.7	230.7	129.5
$N_3P_3K_2$	257.7	241.1	142.5
$N_0P_0K_0$	33.7	34.3	2.1

factor [Nhung and Ponnamperuma 1966; Ponnamperuma *et al.* 1972]. Although iron toxicity can be alleviated by liming and drainage, varietal tolerance is a more simple and economical solution for the small farmers of South and Southeast Asia [Ponnamperuma and Solivas 1981].

A total of 420 rice varieties was screened on an acid sulfate soil in a farmer's field in Albay, the Philippines, during three seasons. Forty-one were found to have tolerance for iron toxicity. Iron toxicity was severe in the wet season, apparently because of strong acidification following the soil drying of the preceding dry season.

Tolerant rice gave grain yields of nearly 3 t/ha when iron toxicity was severe and over 6 t/ha when it was mild. Tolerant varieties may be a substitute for lime on moderately toxic acid sulfate soil [*ibid.*] (Table 16).

Table 16 Iron Toxicity Tolerance Scores and Grain Yield of 15 Selected Rice Varieties on an Acid Sulfate Soil, Malinao, Albay, the Philippines, 1980 Dry Season [Ponnamperuma and Solivas 1981]

Variety/Line	Score at 4 weeks after Transplanting	Grain Yield (t/ha)
IR 4683–54–2	3.0 c	6.7 a
IR 46	4.0 abc	6.4 ab
IR 44	4.0 abc	6.3 abc
IR 50	5.0 abc	6.2 abc
IR 13149–43–2	5.0 abc	6.0 abc
IR 13419–113–1	4.0 abc	6.0 abc
IR 42	5.3 ab	5.9 abc
IR 9129–136–2	3.0 c	5.7 abcd
IR 48	5.7 a	5.6 abcd
IR 52	5.0 abc	5.4 bcde
IR 36	3.7 abc	5.2 cde
IR 4422–480–2	4.7 abc	4.6 def
IR 3839–1	4.3 abc	4.6 def
IR 1444	4.3 abc	4.4 ef
IR 13168–143–1	3.3 bc	3.8 f

Remarks: 1. Values followed by the same letter are not significantly different at the 5% level.
2. The plants were scored for iron toxicity based on foliar symptoms and general appearance on the scale 1 to 9 (1=nearly normal plant; 9=nearly dead or dead plant). A score of 3 or less indicated tolerance; 6 or more indicated susceptibility.

Utilization and Management

1. Chao Praya Delta (Bangkok Plain)

The Chao Praya Delta occupies the southern part of the Central Plain of Thailand. It constitutes the Bangkok Plain, which extends from the Gulf of Thailand in the south to its northern tip in Chainat Province. The altitude of the Chao Praya Delta gradually decreases from 15 m above mean sea level at the apex near Chainat to 5 m at Ayutthaya and 1.5 m near the coast on the gulf. Acid sulfate soils are distributed over 80% of the Bangkok Plain or 800,000 hectares. Almost all of these soils are relatively well developed (Sulfic Tropaquepts).

1.1 Physiographic Regions of the Bangkok Plain

The physiographic regions of Bangkok Plain are illustrated in Fig. 5. The Bangkok Plain is divided into old delta, new delta and fan-terrace complex areas. The area and yield of paddy in the different physiographic regions are shown in Table 17.

1.1.1 Old Delta

This occupies the top part of the delta, extending from the apex of Chainat Province and fanning out to Singburi and Ayutthaya. The elevation attains 20 m near the apex and drops to 5 m along the arc (base line of the boundary). The soils are derived from river alluvium.

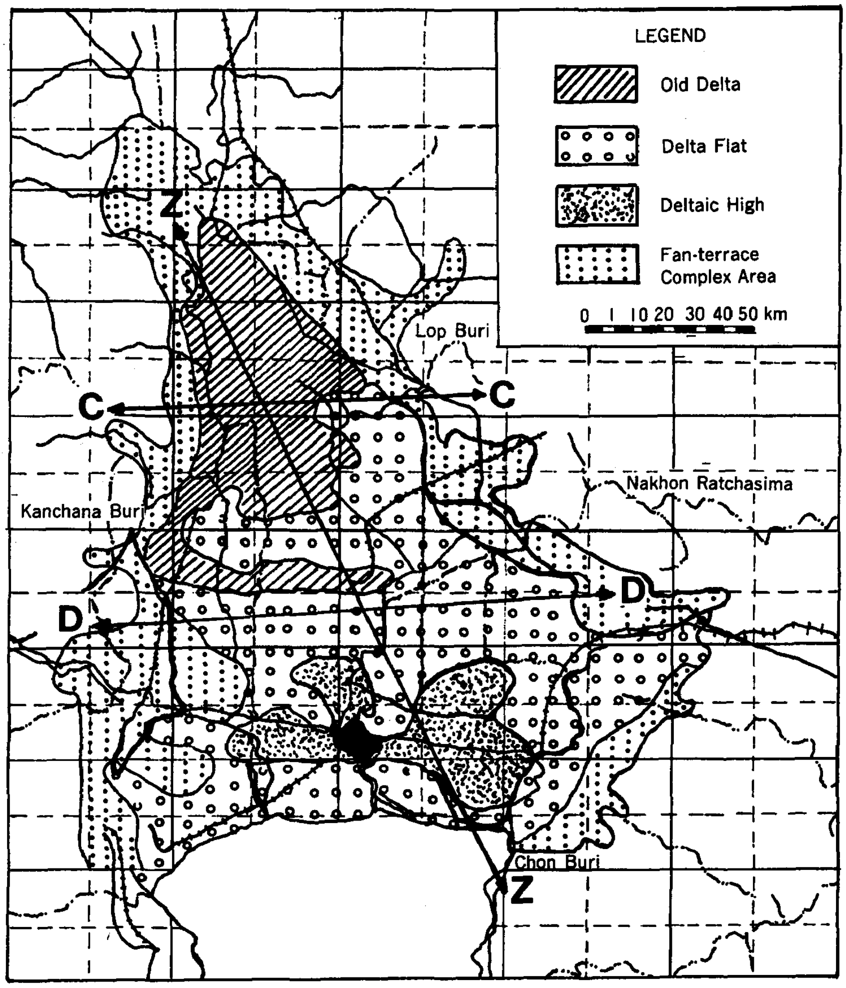

Fig. 5 Physiographic Classification of Paddy Land of the Chao Praya Delta [Vacharotayan 1977]

1.1.2 New Delta

According to Takaya [1969; 1971], this area comprises two physiographic types:

a. Delta flat. This covers almost half of the whole delta (49.4%) and is relatively flat with elevation less than 2 m above mean sea level. All of the acid sulfate soils are within this area, while those western of the Chao Praya River are less severely acidic (P IIa suitability class) than those eastern of the river (P IIIa and P IVa suitability classes).

b. Deltaic high (raised delta). This area is located in the lower part of the delta. It is the slightly elevated part of the new delta, about 1 m higher than the delta flat. Soils are derived from marine sediment and are non-acid marine soils.

1.1.3 Fan-terrace Complex Area

This area has piedmont topography developed along the edge of the Central Plain, where the plain proper rises into the mountain ranges. The soils are derived from river alluvial and colluvial sediments.

1.2 Land Use and Crop Diversification

In 1870, early in the reign of Rama V the vast area west of the Chao Praya River

Table 17 Area and Yield of Paddy in Different Physiographic Regions of the Bangkok Plain as Compared to Other Region of the Central Valley (Modified from Fukui [1973])

Physiographic Regions	Nature of the Soils	Area (× 1,000 ha)	Yield of Paddy (t/ha)
	Central Valley		
Upper Plain	Freshwater alluvium normal soils	1,160	2.32
Bangkok Plain		2,247	1.96
—Old Delta	Freshwater alluvium normal soils	590	1.8–2.2
—Delta Flat	Brackish water alluvium acid sulfate soils	1,110	1.0–1.5
West of	Less severe acidity		Broadcast 1.25–1.5
Chao Praya			Transplant 2.0–2.5
East of	More severe acidity		Broadcast 1.0–1.25
Chao Praya			Transplant 1.25–1.5
—Deltaic High	Marine sediments non-acid marine soils	210	1.8–2.5
—Fan-terrace Complex Areas	River alluvium and colluvium	337	1.0–2.5

in the lower Bangkok Plain began to be developed by the digging of canals for communication and irrigation. Hitherto, much of this area had been uninhabitable and uncultivable due to the high water level in the rainy season and the extreme dryness of the summer. Later, in 1889, King Rama V permitted a private company to invest in the development of an irrigation system by digging a series of canals on the east side of Chao Praya River, the land being subdivided and sold. About 200,000 hectares of land in this area was named the Rangsit Prayurasakdi irrigation and drainage system. The people who moved in to farm the land found later that the soils in this area were very acid and unfavorable for growing crops. Since the digging of the canals, rice has been the only crop grown and yields have been poor, 500–1,500 kg/ha. Farmers living in this area were also poor and largely tenants. Regardless of the fairly well developed irrigation and drainage system, the low productivity of the area and the problem of the soil were not paid any serious attention for more than 80 years since its establishment. Only in 1968, with the aid of the UNDP/SF Project for Strengthening of Soil Survey and Land Classification in Thailand, headed by Prof. Dr. L. J. Pons, FAO consultant, was a pioneer study made of acid sulfate soils in the Central part of the Bangkok Plain.

According to Pons and Kevie [1969], acid sulfate soils of the Bangkok Plain were quite well ripened. These soils need lime to increase the pH and were very low in the availability of two nutrient elements, phosphorus and nitrogen. Physically, these soils are very suitable for rice production. Chemically, however, they cause several serious difficulties. Under very low pH (3.8–4.0) the concentrations of Al^{+3} and Fe^{+2} are high, resulting in toxicity combined with phosphorus deficiency, which cause very poor growth of rice crops. They recommended that the way to improve the acid sulfate soils of the Bangkok Plain and use them most economically was to introduce a second irrigated rice crop in the dry season. Not only would the production of acids in the subsoil then be suppressed, but also, as a consequence, liming and the application of fertilizers would be much more efficient. They commented, however, that it was doubtful if the construction of raised beds for the purpose of horticultural crop would be justified economically.

Owing to the recent rapid growth in the population of the country, and in view of their high agricultural potential, the areas close to the capital which are fairly well furnished with the necessary infrastructure, have been extensively developed as orchards and vegetable farms or raised beds. At present, there are hundreds on orchards, especially tangerine orchards, covering an area of more than 32,000 hectares located on acid sulfate soils of class P IIIa and P IVa. Besides tangerine, farmers grow pomelo, mango, banana, coconut and garden crops such as string bean, water melon, chilli, green cabbage and taro. Most of the garden crops are grown as intercrops between the fruit crops, especially tangerine and pomelo, during the first and second year after planting of the fruit trees.

Fish and shrimp-raising ponds have also been constructed in the acid sulfate soils. Farmers have to drain and flood the newly dug ponds many times and add slaked lime to the water to bring its pH to moderately acid or to neutral. By frequently draining and replenishing the ponds with fresh water from the irrigation canals, healthy and fast-growing cultured fish and shrimps are successfully being raised.

2. *Mekong Delta* (*Vietnam*)

According to the report of Xuan [1983] there are about 2.6 million hectares of potential and actual acid sulfate soils in the Mekong Delta of southern Vietnam; 870,000 hectares of actual acid sulfate soils cover the largest area in the Plain of Reeds and the Plain of Hatian, while 704,000 hectares of potential acid sulfate lie in tidal marshes and mangrove forests. About 1,015,000 hectares are shallowly developed acid sulfate soils in the empoldered backswamps, which are subject to salt water intrusion. Another 27,000 hectares of potential acid sulfate soils are found underneath 0.5–2.0 m of peat mostly in Melaleuca, Avicenia and Rhizophora forest.

2.1 Hydrology

2.1.1 Well-developed Acid Sulfate Soils

During the dry season most soils are not easily reached by river water, for the water table is too low (deeper than 1.5 m), and irrigation is impractical. During the rainy season (rainfall varies from 1,400 to 2,400 mm from May through November) the soils are gradually flooded to a depth of 1–3 m for a period of about three months.

2.1.2 Young and Potential Acid Sulfate

Soils

During the dry season, the young acid sulfate soils are often flushed by river water which is brackish most of the time. Potential acid sulfate soils are flushed daily with saline water due to the tidal movement in the coastal plains. During the rainy season both young and potential acid sulfate soils are flooded to a maximum of about 0.8 m.

2.2 Management and Cropping Systems

In the management of acid sulfate soils for crop production, no single measure can assure success. An integrated system of soil, water and crop management must always be considered in order to optimize the physical, economical as well as social environment without abruptly destroying the natural ecology.

2.2.1 Potential Acid Sulfate Soils

a. Areas with a peaty layer in the top soil. In newly opened Rhizophora and Avicenia forest in coastal marshes, poldering with drainage ditches, and regulating the water level by flapgate at the depth of the pyritic layer were adopted. Pumpkin is planted in the first rainy season and replanted in the second rainy season. Without fertilization it yields about 20 t/ha. Raised beds are made the third year and soybean-corn-soybean is grown during May through December. An alternative to raised beds is to make ridges for sweet potato and intercrop with short-duration high-yielding rice between the ridges.

b. Areas with strong tidal movement affected by brackish or saline water daily. Experienced farmers have exploited these areas by constructing 10-hectare polders to raise shrimps during the dry season, then planting rice in the wet season. Coconuts are grown on the surrounding bunds. Each polder has a network of canals and ditches which serves for drainage during the rainy period and as a catchment pond for raising shrimp fries in the dry period. Every other year they scrape new sediments off on the land surface and pile them onto raised beds. When the raise beds attain an appropriate height, coconuts are planted on them.

2.2.2 Actual Acid Sulfate Soils

a. Empoldered coastal ridges with jarosite deeper than 80 cm. Rice is normally grown by direct broadcasting. Land is prepared for rice after a few rains in the rainy season. Both local and high-yielding varieties are used. The land is normally left fallow during the dry season.

b. Empoldered backswamps with a thin peaty topsoil and jarosite occurring at 10–50 cm depth. Tidal movement is less pronounced. A shallow drainage system is used to grow one rice crop during the rainy season. The system consists of shallow ditches (30–60 cm deep, 60–100 cm wide) spaced at 9-m intervals, forming moderately raised beds. Ditches are connected to a deeper drainage canal to drain water out of the system through a flapgate. The first rain during April will wash acid from the raised bed into the drainage canals, which drain at low tides. The cycle is repeated two or three times before the entire area is naturally flooded. Rice seedlings 40–60 days old (80–100 cm tall) are transplanted on the raised beds, which by then are submerged under 10–40 cm of water. Rice yields 2.5–3.8 t/ha under this system as compared to 0.2–0.5 t/ha on the undrained soils.

c. Trans-Bassac floodplain with a high water table in the dry season and semi-deep water in the wet season. The soil has high organic matter topsoil and clayey subsoil. Water management by gravity with brackish water is possible, and farmers construct polders of various sizes with flapgates to regulate water inside the polders. Raised beds of 5 to 8 m in width separated by ditchs 30–60 cm deep and 50–100 cm wide depending on the depth of jarosite. They are planted with the following crops in sequence.

1. Cassava-rice. Cassava is grown in the dry season (December) and harvested in May. Rice is grown following cassava in the wet season (July–November).
2. Jute or kenaf—rice or wet fallow. Jute is grown during the end of the wet season (December–January), left through the dry season, allowed to resume growth through the wet season, and harvested in August, yielding about 1.5 ton fiber per hectare.
3. Yam—wet fallow. Ridges are made before the first rain and left unplanted throughout the rainy season, when they are submerged. As the flood subsides, the ridges are re-tilled and yam cuttings are planted. Harvesting is done in April, before the rainy season starts.

d. Coastal ridges and Trans-Bassac floodplain with moderate water table during the dry season. Soils are moderately flooded (less than 60 cm) during the rainy season, pineapple and sugarcane are grown with good results. Raised beds are constructed 4–5 m wide and 60 cm higher than the original land surface. The width of the ditches between raised beds varies with the depth of the jarosite layer and the amount of soil required for the raised beds. Beds are left to be leached by rainwater through one whole wet season before pineapple or sugarcane is planted. Irrigation can be carried out with water impounded in the ditches, even if it is acidic. Pineapple usually yields 6–8 t/ha and sugarcane 30–60 t/ha.

e. Trans-Bassac floodplain with a low water table in the dry season but deep flooding in the rainy season, typical of the majority of the Plain of Reeds and the Plain of Hatian. Farmers planted *Melaleuca leucodendron* in the very acidic to extremely acidic zones, and floating rice in the moderately acidic zones. Various agroforestry systems with rice, Melaleuca, bees and fish can be adopted in this area. Acid sulfate soil dynamics require careful planning for land use based on accurate soil survey. The management of the soils for successful crop production requires the following practices and considerations.

1. Early plowing before the soil dries out, to minimize the re-acidification of the surface soil by capillary rise.
2. Well-controlled drainage and irrigation systems.
3. Efficient and appropriate design and

selection of optimal sizes of polders, drainage ditches and canals, and raised beds, optimal kinds and amounts of chemical amendments, and the most suitable and economic crops for each type of acid sulfate soils.

3. *Rapid Reclamation of Fishponds in Acid Sulfate Soils in the Philippines*

The extent of acid sulfate soils in the Philippines is less than half a million hectares, which is under mangrove forest, paddy fields and fishponds. In recent years, fishponds have increased rapidly in area at the expense of mangrove and paddy fields and presently are the most important form of land use in the coastal acid sulfate areas of the Philippines [Brinkman and Singh 1981].

3.1 Problems Faced by Fishpond Operators in Acid Sulfate Areas

The main problems arising after construction or deeper excavation of fishponds in acid sulfate soils are the insufficient growth of algae, the poor condition and consequent slow growth of the fish, the hazard of sudden fish kills during rain after dry periods and, even if these are solved, the very low efficiency of phosphate fertilizers as normally applied.

The growth of the algae is inhibited or retarded by the low pH of the water, the high aluminum and the low phosphate concentrations. The low pH and the high aluminum concentrations may kill or, in less severe cases, weaken the fish making them prone to diseases and parasites. The sudden influx of acid and aluminum salts from the dikes during rains after a dry period causes an ionic imbalance in the fish. This stress is commonly lethal to a large proportion of the population. Finely divided ferric hydroxide subsequently appears in the water and clogs the gills of the survivors, killing another contingent and weakening the remainder.

A lesser problem is the erosion of the dikes during heavy rains owing to the lack of a good vegetation cover on the acid, toxic soil for the first five to 10 years.

3.2 Reclamation Efforts

3.2.1 Treatment of the Pond Bottom

This is affected by allowing the bottom of the pond to dry, plow to 10 cm depth, then harrowing to small clods (not into a powder). After allowing to dry for 2–3 weeks, brackish or salt water (pH 7–9) is brought in to fill the pond. When pH of the water drops to 3–4, the pond is drained and refilled with new brackish or saline water. This process is repeated until the pH of the pond water remains constant at a value just below 5 (4–6 refills). The pond is then drained and the bottom allowed to dry out completely. The pond bottom is plowed and harrowed and the process of filling and draining is repeated until the pH of water remains constant at 5 (1–3 drying cycles). The pond is then drained, and about 1/2 t/ha of lime ($CaCO_3$) is broadcast over its bottom which should not be incorporated with the soil. The pond is then ready for the start of normal raising operation.

3.2.2 Treatment of Dikes

The dikes crest should be leveled and small bunds or levees constructed along the sides of the crest to collect water. The crest of the dikes are flooded with brackish or saline water at 10 cm depth and the level is maintained by refilling throughout the period of pond treatment. When the pond bottom is ready to be dried, the top of the dikes should also be allowed to dry by draining out the water. The top of the dike is flooded again during the next cycle of filling and draining the pond, the depth of water again being maintained at 10 cm. The levees are then removed by levelling, lime is applied to the crest and the side of the dike. Weeds are allowed to grow or grass can be planted to cover the dikes to protect against erosion, acid formation and leaching.

3.2.3 Improvement of Phosphorus Status

To decrease the rate of phosphate fixation during the growing season, silica-rich materials such as decomposed rice hull may be broadcast over the pond bottom to bind aluminum activity. Chicken manure is distributed over the pond bottom before the pond is filled. After a few days, nitrogen and phosphorus fertilizers are broadcast in the pond water. Phosphorus should be applied frequently in small quantities.

Literature Cited

Andriesse, J. P.; van Breemen, N.; and Blokhius, W. A. 1972. The Influence of Mud Lobster (*Thallasina anomale*) on the Development of Acid Sulfate Soils in Mangrove Swamps in Sarawak (East Malaysia). *Proc. of the International Symposium on Acid Sulfate Soils*. 13–20 August 1972. Wageningen, Netherlands.

Attanandana, T. 1982. Fertility Problems of Acid Sulfate Soils of Thailand. Ph. D. Thesis. Kyoto: Kyoto University. 210pp.

Attanandana, T.; and Vacharotayan, S. 1983. Rock Phosphate Utilization on Acid Sulfate Soils of Thailand. *Int. Seminar on "Ecology and Management of Problem Soils in Asia."* Nov. 8–11, 1983.

Attanandana, T.; Petchayapisit, J.; and Patrick, W. H., Jr. 1985. Factors Affecting Amelioration of the Oxidized Potential Acid Sulfate Soil for Rice Cultivation. *Proceedings of the International Seminar on "Environmental Factors in Agricultural Production."* 1985. Thailand.

Attanandana, T.; Vacharotayan, S.; and Kyuma, K. 1981. Chemical Characteristics, and Fertility Status of Acid Sulfate Soils of Thailand. *Proc. International Symposium on Acid Sulfate Soils*. Jan. 18–30, 1981. Bangkok, Thailand.

Bloomfield, C.; and Coulter, J. K. 1973. Genesis and Management of Acid Sulfate Soils. *Advances in Agronomy* 25. New York; London: Academic Press, Inc.

Brinkman, R.; and Singh, V. P. 1981. Rapid Reclamation of Brackish Water Fishponds in Acid Sulfate Soils. *Proc. International Symposium on Acid Sulfate Soils*. Jan. 18–30, 1981. Bangkok, Thailand.

Fukui, H. 1973. Environmental Determinants Affecting the Potential Productivity of Rice: A Case Study of the Chao Phraya River Basin of Thailand. Doctoral Dissertation of Kyoto University. Cited in Vacharotayan [1977].

Goldhaber, M. B.; and Kaplan, I. R. 1974. The Sulfur Cycle. In *The Sea, Vol. 5, Marine Chemistry*, edited by E. D. Goldberg, pp. 627–655. New York: Wiley-Interscience. Cited in van Breemen [1982].

Hesse, P. R. 1961. The Decomposition of Organic Matter in a Mangrove Swamp Soil. *Plant and Soil* 14(3): 249–263.

IRRI (International Rice Research Institute). 1963. *Annual Report 1963*. Los Baños, Laguna: Int. Rice Res. Inst.

Kawalec, A. 1972. World Distribution of Acid Sulfate Soils. References and Map. *Proc. of the International Symposium on Acid Sulfate Soils*. 13–20 August 1972. Wageningen, Netherlands.

Kevie, W. van der. 1972. Physiography, Classification and Mapping of Acid Sulfate Soils.

Proc. of the International Symposium on Acid Sulfate Soils. 13–20 August 1972. Wageningen, Netherlands.

Kevie, W. van der; and Yenmanas, B. 1972. Detailed Reconnaissance Soil Survey of Southern Central Plain Area. *Soil Survey Report.* No. 89. Bangkok: Department of Land Development.

Khouma, M.; and Touré, M. 1981. Effects of Lime and Phosphorus on the Growth and Yield of Rice in Acid Sulfate Soils of the Casamance (Senegal). *Proc. International Symposium on Acid Sulfate Soils.* Jan. 18–30, 1981. Bangkok, Thailand.

Kosaka, J. 1971. Report on Acid Sulfate Soils in the Muda Irrigation Area. (Japanese, English Summary) *Trop. Agric. Res. Center (Japan) Bull.* 17: 29. Cited in van Breemen [1982].

Le van Can. 1981. Rock Phosphate in Rice Production on Acid Sulfate Soils in Vietnam. *Proc. International Symposium on Acid Sulfate Soils.* Jan. 18–30, 1981. Bangkok, Thailand.

McWilliam, J. P. 1984. The Possibilities of Using Marl to Improve Acid Sulfate Soils in the Southern Central Plain of Thailand. *Report.* Bangkok: Department of Land Development, Ministry of Agriculture and Cooperatives. 100pp. (Mimeographed)

Moormann, F. R. 1961. Research on Acid Sulfate Soils and Their Amelioration by Liming. *Report.* Saigon: Agronomic Library, Ministry of Rural Affairs. pp. 3–15.

Moraghan, J. T.; and Patrick, W. H., Jr. 1974. Selected Metabolic Processes in a Submerged Soil at Controlled pH. *Int. Congr. Soil Sci. Trans. 10th (Moscow)* II: 264–268.

Nhung, M. T. M.; and Ponnamperuma, F. N. 1966. Effects of Calcium Carbonate, Manganese Dioxide, Ferric Hydroxide and Prolonged Flooding on Chemical and Electrochemical Changes and Growth of Rice in a Flooded Acid Sulfate Soil. *Soil Sci.* 102: 29–41.

Osborne, J. F. 1984. Soil Analysis as a Guide to Acidity Classes in Mature Acid Sulfate Soils of the Southern Central Plain of Thailand. *Proceedings of the 5th ASEAN Soil Conference on "Soil Science as a Tool for Rural Development."* 10–23 June 1984. Bangkok, Thailand.

Parischa, N. S.; and Ponnamperuma, F. N. 1976. Influence of Salt and Alkali on Ionic Equilibria in Submerged Soils. *Soil Sci. Soc. Am. J.* 40: 374–380.

Pham-Huu-Anh; Moormann, F. R.; and Golden, J. D. 1961. Liming Experiments on Acid Sulfate Soils. *Researches on Acid Sulfate Soils and Their Amelioration by Liming.* Ministry of Rural Affairs.

Ponnamperuma, F. N. 1964. Dynamic Aspects of Flooded Soils and the Nutrition of the Rice Plant. *Proc. Sym. Mineral Nutr. Rice Plant.* Maryland: John Hopkins Press. 494pp.

Ponnamperuma, F. N.; and Solivas, J. L. 1981. Varietal Reactions of Rice to Iron Toxicity on an Acid Sulfate Soil. *Proc. International Symposium on Acid Sulfate Soils.* Jan. 18–30, 1981. Bangkok, Thailand.

Ponnamperuma, F. N.; Attanandana, T.; and Beye, G. 1972. Amelioration of Three Acid Sulfate Soils for Lowland Rice. *Proc. of the International Symposium on Acid Sulfate Soils.* 13–20 August 1972. Wageningen, Netherlands.

Ponnamperuma, F. N.; Bradfield, R.; and Peech, M. 1955. Physiological Disease of Rice Attributable to Iron Toxicity. *Nature* 175: 265.

Pons, L. J.; and Kevie, W. van der. 1969. Acid Sulfate Soils in Thailand. *Soil Survey Reports of the Land Development Department.* Ministry of National Development.

Pons, L. J.; van Breemen, N.; and Driessen, P. M. 1982. Physiography of Coastal Sediments and Development of Potential Soil Acidity. *Acid Sulfate Weathering.* SSSA Special Publication Number 10. Madison, Wisconsin: Soil Sci. Soc. of America.

Rorison, I. H. 1972. The Effect of Extreme Soil Acidity on the Nutrient Uptake and Physiology of Plants. *Proc. of the International Symposium on Acid Sulfate Soils.* 13–20 August 1972. Wageningen, Netherlands.

Solivas, J. L.; and Ponnamperuma, F. N. 1982. Improving Rice Yields on Acid Sulfate Soils. *Report of the 13th Annual Scientific Meeting of the Crop Science Society of the Philippines.* April 28–30, 1982. Cebu City: Lahug.

Sombatpanit, S. 1970. Thesis. Uppsala: Royal Agriculture College. Cited in Bloomfield and

Coulter [1973: 265–326].

Takaya, Y. 1969. Topographical Analysis of the Southern Basin of the Central Plain, Thailand. *Southeast Asian Studies* 7(3). Kyoto University. Cited in Vacharotayan [1977].

———. 1971. Two Blackish Clay Beds along the Chao Phraya River of Thailand. *Southeast Asian Studies* 9(1). Kyoto University. Cited in Vacharotayan [1977].

Tanaka, A.; and Navasero, S. A. 1966. Growth of the Rice Plant on Acid Sulfate Soils. *Soil Sci. and Plant. Nutr.* 12(3): 23–30.

USDA, Soil Survey Staff, Soil Conservation Service. 1975. Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys. *USDA Agric. Handb.* 436. Washington, D.C.: US. Government Printing Office. 754pp. Cited in van Breemen [1982].

Uwaniyom, J.; and Charoenchamratcheep, C. 1984. Liming of Acid Sulfate Soils in the Bangkok Plain. *FFTC Book Series.* No. 17. Taiwan: Food and Fertilizer Technology Center for the Asian and Pacific Region.

Vacharotayan, S. 1977. *Acid Sulfate Soils of Thailand.* Bangkok: Department of Soils, Kasetsart University. (in Thai)

Vamos, R. 1967. *Soil Fert.* 30, 2438. (abstr.)

van Breemen, N. 1971. Methods of Analysis. *Laboratory Information Paper.* No. 3. Bangkok: Soil Survey Division.

———. 1975. Acidification and Deacidification as a Result of Flooding. *Soil Sci. Soc. Amer. Proc.* 39: 1153–1157.

———. 1982. Genesis, Morphology and Classification of Acid Sulfate Soils in Coastal Plains. *Acid Sulfate Weathering.* SSSA Special Publication Number 10. Madison, Wisconsin: Soil Sci. Soc. of America.

van Breemen, N.; and Pons, L. J. 1978. Acid Sulfate Soils and Rice. *Soils and Rice.* IRRI. pp. 739–761.

Watts, J. C. D. (1969). *Malay Agr. J.* 47: 187–202. Cited in Bloomfield and Coulter [1973].

Xuan, Vo-Tong. 1983. Present Land Use in Potential and Actual Acid Sulfate Soils in the Mekong Delta. *Proceedings of the 4th International Forum on Soil Taxonomy and Agrotechnology Transfer.* Bangkok, Thailand.

Xuan, Vo-Tong; Quang, N. K.; and Tri, L. Q. 1981. Rice Cultivation on Acid Sulfate Soils in the Vietnamese Mekong Delta. *Proc. International Symposium on Acid Sulfate Soils.* Jan. 18–30, 1981. Bangkok, Thailand.